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Assessing the cost of biofuel production with increasing penetration of the transport fuel market: A case study of gaseous biomethane in Ireland

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ABSTRACT

Biomethane is an indigenously produced gaseous sustainable transport fuel that uses organic feedstock. Allowing for a realistic collection of organic residues and grass silage from 2.5% of pasture land would allow Ireland to generate 17% renewable energy supply in transport (RES-T) and surpass its 10% target for renewable transport energy by 2020. This would significantly lessen Ireland's dependence on imported fossil fuels, allow compliance with the EU Landfill Directive, and reduce pollution of waterways. Biomethane generated from the organic fraction of municipal solid waste (OFMSW) is the cheapest biomethane (€0.36/L diesel equivalent including for value added tax (VAT) of 21%) This is the least expensive fuel because of the associated gate fee of €70/t. If no gate fee were available the cost would be €1.35/L diesel equivalent including VAT: this underlines the importance of gate fee to what is primarily a waste treatment system. Biomethane from slaughter house waste (SHW) is estimated at €0.65/L diesel equivalent while biomethane produced from grass and slurry is more costly to produce (€1.40/L diesel equivalent). This is still in the cost range of petroleum derived transport fuels at the service station (diesel and petrol prices ranging from €1.38 to 1.45/L in February 2011). OFMSW and SHW can between them provide 1.4% RES-T at a minimum cost of €0.52 /L. To achieve 10% RES-T biomethane will cost a minimum of €1.28/L diesel equivalent. Gaseous fuel can be more competitive by considering a blend of biomethane and natural gas (BioCNG) (e.g. 20% biomethane with 80% natural gas). If natural gas at approximately €0.7/L diesel equivalent is considered, BioCNG will cost €0.82/L at the 10% RES-T target.

Contents

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1. Introduction

1.1. Transport energy in Ireland

In the period 1990–2009 Ireland experienced substantial expansion of the transport sector with an increase in final energy consumptions of approximately 150% over the period [1]. Since 2008 there has been a decrease in transport growth which is related to the downturn of the Irish economy; however transport continues to consume over a third of primary energy and accounts for 41.4% of total final consumption [1]. Imported petroleum products account for approximately 98% of transport energy, while biofuel penetration has increased somewhat to 1.8% of petrol and diesel sales in 2009. To accelerate the growth of renewable energy in transport, the Irish Government recently changed the support mechanism from excise relief on biofuel producers, to a biofuels obligation on transport fuel suppliers. The initial biofuels obligation is set at 4% by volume of biofuel as a proportion of road fuel sold [2] and aims to increase the biofuels proportion to a level that will comply with the 10% renewable energy in transport (RES-T) target for 2020. The Irish government also has a target of 10% electric vehicles (EV's) by 2020; however this is expected to meet only 1% RES-T, therefore biofuels will account for the outstanding 9% RES-T [3].

1.2. Biofuel concerns

Ireland's arable land (9% of total agricultural land) is already fully utilised for food and beverage production and the conversion of permanent pastureland to arable required by most energy crops (such as sugar beet and rape seed) is restricted by EU agricultural policy. As a result the majority of ethanol and biodiesel is imported. Questions pertain as to how Ireland can fulfil its biofuels target and meet the criteria for sustainable biofuels as set out in the EU Renewable Energy Directive [4]. An additional obstacle in developing an indigenous biofuels industry in Ireland relates to the fact that Ireland imports approximately 66% of its transport fuel from the UK [5]. This imported fuel already contains 4% biofuels in accordance with the UK's Renewable Transport Fuel Obligation [6] and by default also fulfils 2.64% of the 4% Irish biofuels obligation. As the UK imports the majority of its biofuel (e.g. 80% bioethanol from Brazil and 38% biodiesel from the USA) [7], there is some concern about the sustainability associated with this practise and the reported negative environmental effects on sensitive eco-systems [8]. As the EU Renewable Energy Directive stipulates that biofuels must not harm sensitive eco-systems it is suggested that national government policy should re-focus attention on the development of sustainable indigenous biofuels.

1.3. Energy forecasts for Ireland

Ireland's energy forecasts for 2020 have been revised a number of times since 2008 [3,9] to incorporate the effects of sharp economic decline but also to allow for energy savings associated with Ireland's National Energy Efficiency Action Plan (NEEAP) and the implementation of the National Renewable Energy Action Plan (NREAP). In the most recent energy forecasts for Ireland to 2020 [3] the baseline scenario for total final energy in transport is 187 PJ, while the NEEAP/NREAP scenario is 178 PJ. The latter assumes Ireland will meet its overall target of renewable energy supply (RES) of 16% and also the renewable energy supply in Transport (RES-T) of 10%. This projection (178 PJ) will be assumed in the analysis below.

1.4. Greenhouse gas emissions and related EU Policy

In 2008, Ireland's major contributor to GHG emissions was agriculture (27.3% of GHG emissions) followed by industry and transport (21.8%, 21.1% respectively) [10]. The European Commission (EC) has proposed new emission targets for 2020 which will replace Kyoto when it expires in 2012 [11]. The target set for Ireland is 20% less emissions by 2020 relative to 2005. This is a significant target as can be evidenced by Ireland's difficulty in meeting its targets under the Kyoto protocol. Ireland's GHG emissions are 26% above the 1990 level [10], while the committed target allows for only a 13.5% increase in GHG emissions.

The EU Renewable Energy Directive [4] has highlighted the sustainability of biofuel production and set GHG savings targets compared to conventional fuels such as petrol and diesel. Article 17 states that "The GHG emission saving from the use of biofuels and bioliquids ... shall be at least 35% ... from 2017 GHG emission savings shall be at least 50%". According to the same directive biomethane produced from wastes and residues readily meet the requirement through GHG savings of 75–85% which may not be said for many first generation indigenous liquid biofuels. As a result many European countries are assessing biofuel systems that will satisfy the required GHG savings and fulfil the sustainability criteria set out in the directive. Ireland's waste disposal problem is increasing with time and according to the EU Landfill Directive [12] alternative waste management options other than landfill must be implemented for over 1 million tonnes of OFMSW by 2016. The diversion of municipal, industrial and agricultural waste towards the production of biofuel will help Ireland to meet the RES-T targets, satisfy the Landfill Directive, reduce pollution and eutrophication and reduce dependence on expensive imported fossil fuels.

1.5. Biogas, a source of biofuel

Biogas is the major energy output from anaerobic digestion (AD), where organic waste and wet biomass (e.g. energy crops) are

Table 1
Energy potential of biomethane in Ireland to meet RES-T 2020 target.

Feedstock	Practical energy potential in 2020 (PJ)	Including RES-T factor (x2) (PJ)	Percentage of final energy in transport
OFMSW	0.57	1.14	0.64%
Slaughter waste	0.68	1.36	0.76%
Agricultural slurry	1.88	3.76	2.12%
Grass silage	11.90	23.79	13.36%
Total	15.03	30.05	17%

converted to a gaseous biofuel. Various organic wastes can be used as feedstock, such as the organic fraction of municipal solid waste (OFMSW), slaughter house waste (SHW), agricultural slurries and wet biomass such as ensiled energy crops [13]. Besides the production of energy (in the form of biogas), AD also produces an organic fertiliser with lower pollution potential and significantly better availability of nutrients when compared to slurries [14]. By using the digestate as fertiliser, the goal of a sustainable cropping system can be achieved [15,16].

Traditionally biogas has been used in on-site combined heat and power plants (CHP); heat and electricity may be used on-site or electricity may be exported to the grid and the heat exported via a district heating system. In 2010 the renewable energy feed-in tariff (REFIT) for electricity offered 15 c/kW h for biogas facilities producing less than 500 kW_e and 13 c/kW h for larger facilities. It has been suggested that the present feed in tariff structure is not economically attractive for investors as it does not take into consideration the cost of producing energy crops such as grass silage [5]. Small scale biogas CHP plants (less than 500 kW_e) offer efficiencies of 30–40% electricity and 35–45% heat [17]. It is argued that on site CHP generation is not the most efficient use of biogas unless a market can be found for the heat produced [5]. It has been demonstrated in countries such as Germany, Sweden, and Switzerland that a more efficient use of biogas can be achieved through upgrading biogas to biomethane. Biomethane can then be injected into the gas grid or used as a transport fuel in compressed natural gas (CNG) vehicles. Gases such as CO_2 and H_2S are eliminated and as a result the CH_4 content is raised to ca. 97%. The end product is practically identical to natural gas and can be blended as BioNG or sold separately [18]. The existing natural gas infrastructure allows for an efficient distribution system with the possibility to sell the biomethane anywhere on the gas grid.

1.6. Bio-resources suitable for biomethane production in Ireland

As 91% of Ireland's agricultural land is under grass it has been shown that grass silage has the most potential as an indigenous feedstock to meet Ireland's renewable heat and transport obligations for 2020 [19]. Approximately 1% of the EU population live in Ireland; however the country is home to 8% of the total EU cattle herd. The quantity of agricultural slurry which is land spread is in excess of 40 million tonnes annually. This slurry is a major source of eutrophication, air pollution and toxicity in rivers, streams and lakes in the country. Nevertheless, current agricultural practice allows for slurry and slaughter waste to be spread over pasture and tillage land respectively. A study of Ireland's bioresources by Singh and co-workers suggests that there is potential to generate 15 PJ/a biomethane from animal slurries, the organic fraction of municipal solid waste (OFMSW), slaughterhouse waste (SHW) and surplus grass. It is estimated that 5.3 Mt/annum of grass (i.e. 2.5% of pastureland) and 3.87 Mt/annum of slurry (which corresponds to 12% of projected slurry production) would be readily available for AD by 2020. Other feedstocks such as OFMSW and SHW also present a great opportunity for biogas. Additionally, they attract a gate-fee and have relatively high biogas yields, thus improving the economics and efficiency of the system. It is conservatively predicted that 25% of the organic fraction of municipal solid waste and 50% of slaughter house waste will be available for biogas production by 2020 [13]. Assuming the latest energy projections for transport in 2020 [3], 10% RES-T will equate to 17.8 PJ, biomethane can supply 8.4% of energy in transport. By allowing for the double credit weighting of biofuels from wastes and lignocellulosic material under the Renewable Energy Directive [4] biomethane can readily provide 17% RES-T without impinging on food supply, therefore exceeding the RES-T 10% target for 2020 as shown in Table 1.

1.7. Focus of the paper

The objective of this paper is to assess the economics of producing biomethane for use as a transport fuel from various bioresources while also assessing the relationship between increased penetration of biomethane in the transport sector and production cost. The cost of biomethane production to meet the 10% RES-T target for 2020 is sought. This paper builds upon two previous papers: one which assessed the bioresource for biomethane production in Ireland [13]; the second evaluated the cost of mono-digestion of grass silage at farm scale [20].

2. Background and methodology

2.1. Methodology

Much of the cost analysis is based on existing biomethane facilities in Europe, data taken from scientific literature, discussions with industry and case studies. The case studies are not named as facilities are commercially sensitive. A simple economic analysis is carried out which assesses the total cost of producing a unit of biomethane based on a minimum breakeven price yielding a return on investment of 6% over 15 years. The cost of producing biomethane for sale as a transport fuel can be divided into three major process steps; biogas production, biogas upgrading to biomethane and distribution of biomethane. Each step of the process will be discussed in detail.

2.2. Functional unit

For biomethane systems, the major output is biomethane and therefore the functional unit of annual production is measured in m_n^3 biomethane per annum. However, the capacity of the upgrading facility is usually measured in m_n^3/h of raw biogas. The economic analysis uses the functional unit of €/kW h and €/m^3 product gas (i.e. biomethane at 97% CH_4) for comparing the operating costs of the system; 1 m_n^3 biomethane has an energy value of 36.6 MJ or 10.2 kW h. Typically 1 m_n^3 of biomethane equates to 1 L of diesel.

2.3. A biogas/biomethane strategy for Ireland

In order to benefit from economies of scale, the centralised anaerobic digester (CAD) model has been proposed. The CAD model usually employs biogas plants in the range of 20,000–80,000 t/a of feedstock [21]. A minimum size of a CAD is assessed here as suggested by Singh et al. [13] at 50,000 t/a biomass feedstock; however the optimum size of a biogas facility is very much dependant on

the substrate properties and its availability within the surrounding area of the biogas plant [17]. The following three scenarios will be investigated to demonstrate the large variation in cost associated with biomethane from different feedstocks; Scenario 1: Examines biomethane from agriculture: Grass Silage and Animal Slurry. Scenario 2: Biomethane from meat rendering residues – slaughter house waste (SHW). Scenario 3: Biomethane from domestic and commercial food waste – the organic fraction of municipal solid waste (OFMSW).

2.4. AD plant – biogas production technologies

The type of technology used to convert organic substrate to biogas is of critical importance to the efficiency of the process [22,23]. Substrates with a low dry solids content (i.e. less than 15% DS) such as agricultural slurries and SHW are suited to a wet technology such as a continuously stirred tank reactor (CSTR), this can be a one or two stage process. Feedstocks with higher DS content may also be incorporated by diluting with water or a low solids co-substrate [23,24]. OFMSW with a DS of approximately 30% may be better suited to a dry technology such as the dry continuous or batch process. In the dry batch process a series of batch chambers are sequentially loaded to give a relatively constant rate of biogas output. The dry continuous process usually involves higher technical specifications than the batch, with greater automation. In countries with well established biogas expertise (e.g. Germany) biogas technology providers supply standardised units which have been optimised for biogas production for a range of substrates (e.g. maize silage) [25]. In the analysis of each scenario, a particular AD technology is suggested for the relevant substrate.

2.5. Biogas upgrading technology

The major difference between biogas and natural gas is in relation to CO_2 content. Biogas usually contains 30–40% CO_2 and 55–70% CH_4, while natural gas consists primarily of methane with small proportions of propane and butane depending on the blend and standards. Biogas also contains small quantities of water vapour, hydrogen sulphide, nitrogen, oxygen, ammonia, siloxanes and particles. The feedstock determines the concentration of the impurities and gases in the biogas. For efficient operation, for protection of mechanical equipment from corrosion, and to maximise the volumetric energy density, contaminants and gases with no energy value need to be removed [24].

For most upgrading systems removal of hydrogen sulphide prior to upgrading is necessary. This is usually achieved by addition of iron hydroxide to the digester; if larger quantities of hydrogen sulphide are present in the biogas (i.e. greater than 2000 ppmv) the use of a H_2S bio-scrubber may be necessary before CO_2 removal (depending on upgrading technology). There are various techniques and methods for CO_2 removal which involve cooling, compression, precipitation, absorption or adsorption to upgrade the biogas The three most commercially available upgrading techniques are high pressure water scrubbing (HPWS), pressure swing adsorption (PSA) and chemical (amine) scrubbing. To avoid the contamination of the end product, standards have been set in a number of European countries (e.g. Germany, Sweden, and Switzerland) with limits on certain components such as oxygen, water dew point, particles and sulphur. According to Persson et al. [26] it is possible to achieve these standards by using existing upgrading processes. HPWS and PSA systems are currently the dominant upgrading systems in the biomethane industry. HPWS systems were identified as being the least complex in operation and therefore are currently the most economically attractive and most employed systems in Europe [27]. Therefore HPWS is assumed as the upgrading technology in this analysis as plants are commercially available from several suppliers in a broad range of capacities [24]. HPWS does not require heat input to the process, operates on approximately 0.25 kW h_e/m^3 of raw biogas input and can also remove H_2S. Methane losses are reported as being approximately 1.5% [24,25].

The fundamental operating principle of the HPWS system is that carbon dioxide has a higher solubility in water than methane, particularly at lower temperatures and will therefore be dissolved to a higher extent. In the scrubber column, carbon dioxide is dissolved in the water and thus the methane concentration in the gas phase increases. The water leaving the absorption column is transferred to a flash tank where the dissolved gas, which contains mostly carbon dioxide but also some small amount of methane (~1.5%), is combusted to mitigate any possible methane release to the atmosphere. If higher amounts of methane are present in the exhaust gas (i.e. greater than 1.5%) it is transferred back to the raw gas inlet. The water is cooled down to achieve the large difference in solubility between methane and carbon dioxide before it is recycled back to the absorption column. The extracted heat can be used by the biogas plant to help meet thermal demand.

2.6. Scenario 1: grass and slurry

Grass yields in Ireland are relatively high in comparison to central European countries due the cool temperature oceanic climate [5]. Perennial rye grass, which is the dominant grass type in Irish pastureland, has an average yield of 12 tDS/ha [28] and is usually preserved in a horizontal silo commonly known as a silage pit, such grass silage has a dry solids content of approximately 22%, of which 90% are volatile [29]. In this analysis a methane yield of 300 m^3 CH_4/tVS added (at 55% methane content) is assumed (i.e. 108 m^3/t) [20]. It should be noted that higher methane yields have been reported in literature e.g. Thamsiriroj and Murphy [29] reported 440 m^3 CH_4/tVS using perennial rye grass in a wet continuous two stage process with a solid retention time of 60 days. Asam and co-workers reported methane potential of 361 m^3 CH_4/tVS for grass silage from a laboratory batch test [30], while Nizami and co-workers reported a methane yield of 305 m^3 CH_4/tVS from a sequencing leach bed reactor coupled with an upflow anaerobic sludge blanket [31]. Grass has specific characteristics such as its long fibrous nature and its tendency to float which can lead to inhibition of the biological process [32]. In continental Europe grass is usually co-digested with a larger proportion of maize or animal slurry, however maize requires tillage land to grow and is better suited to a continental climate. Therefore, based on the practical collectable quantities of grass and slurry at national level, as outlined above, it is suggested that an agricultural based biogas plant would co-digest grass and slurry at a ratio of 3:2.

The composition and concentration of animal slurries can vary considerably depending on livestock, type of animal feed, farming methods, age and storage of slurry. Cattle slurry is freely available in vast quantities with a solids content ranging from 6% to 12% DS. While pig slurry is more dilute generally 3–9% DS. In Ireland cattle are generally housed only for winter months (maximum 20 weeks) while pigs are generally kept indoors throughout the year. Taking this into consideration it may be more feasible to use pig slurry to ensure a constant supply of feedstock. Pig slurry has an average methane yield of approximately 0.32 m^3 CH_4/kg VS_{added}, however due to the dilute nature of slurry it has a low volumetric biogas yield per tonne feedstock (i.e. 22 m^3/t slurry) [30,33]. Slurry lends itself to a co-digestion process utilising a wet technology such as a one or two stage CSTR. From a technical and economic viewpoint the use of a co-substrate with high biogas yields per tonne (e.g. grass silage or OFMSW) is necessary to increase biogas production rates. However, from an environmental protection viewpoint, the use of animal slurry in biogas plants should be encouraged as a waste treatment process for the large quantities produced in agriculture.

Table 2
Energy yields from grass silage and slurry.

Total feedstock	50,000	t/a	
Grass silage			
Annual grass feedstock	30,000	t/a	1.5: 1 ratio of grass silage to slurry
Total yield of DS	6600	tDS/a	22% DS average for pit silage
Total yield of VS	5940	tVS/a	90% VS in grass silage
Yield of grass silage	12	tDS/ha	Average grass yields in Ireland
Total area under grass	550	Ha	Land required for grass
Gross yield of CH_4	1,782,000	m^3/a	300 m^3 CH_4/tVS
Gross biogas yield	3,240,000	m^3/a	55% CH_4
Gross energy from grass	67,324	GJ	37.78 MJ/m^3
Pig slurry			
Annual slurry feedstock	20,000	t/a	
Total yield of DS	1200	tDS/a	6% DS in pig slurry
Total yield of VS	900	tVS/a	75% VS
Gross yield of CH_4	288,000	m^3/a	320 m^3 CH_4/tVS
Gross biogas yield	443,077	m^3/a	65% CH_4
Gross energy from slurry	10,881	GJ	
Grass silage and pig slurry			
Total gross biogas yield	3,683,077	m^3/a	
Average rate of biogas production	460	m^3/h	8000 h/annum
Total CH_4 yield	2,070,000	m^3/a	
Losses in upgrading	31,050	m^3/a	1.5%
Net CH_4 yield	2,038,950	m^3/a	
Total biomethane yield	2,102,010	m^3/a	97% CH_4
Total energy yield	77,032	GJ/a	37.78 MJ/m^3
Percentage energy from grass silage	87	%	

In addition, the use of fresh animal slurry is an ideal co-substrate for grass silage due to the presence of digestive tract bacteria and enzymes in the slurry [14]. The energy yield from the co-digestion of 30,000 t grass silage and 20,000 t of slurry is mostly influenced by the grass portion as shown in Table 2 (87% of energy comes from grass).

2.7. Scenario 2: SHW

The total number of livestock (i.e. cattle, pigs and sheep) slaughtered in Ireland is estimated to be about 9 million annually [34]. The energy potential from the waste products associated with the meat rendering process is outlined in detail by Thamsiriroj and Murphy [34]. Due to the importance of the agricultural and food sector to the Irish economy, the Department of Agriculture, Food and Forestry (DAFF) has published a strict list of permitted feedstock's [35], which fall under the animal by-products (ABP) regulations [36] for use in biogas plants. With regards to SHW, DAFF allow digestive tract content separated from the digestive tract to be used in biogas plants. Such paunch content, often referred to as belly grass, is highly amenable to AD and biogas production. Paunch content is assumed to have a DS of 11% and VS of 80%, with 85% VS destruction [34]. Thus a relatively high methane yield of 440 m^3 CH_4/tVS (i.e. 75 m^3 biogas/t) is used in calculating the biogas yields from SHW (energy yields are calculated similar to method shown in Table 2). A similar biogas plant treating SHW in Sweden reported biogas yields of approximately 105 m^3 biogas/t; therefore the biogas yields assumed in this analysis can be viewed as conservative. Other SHW wastes such as offal and process water are also amenable to biogas production and may be treated on site subject to DAFF approval. The use of processed animal protein and fats (i.e. tallow) are also allowed under the ABP but these already have markets in bio-diesel production [18] and are not considered for biogas production.

2.8. Scenario 3: OFMSW

OFMSW refers to all domestic and commercial food and garden waste [37]. At present the collection and treatment of OFMSW is a topic of much debate in Europe with some member states encouraging source segregation and recycling of waste material (e.g. Germany and Spain) while other countries (such as France and UK) are more in favour of centralised waste separation. With regards to using OFMSW as a substrate for biogas production such concerns can have a profound effect on the type of system required and the costs involved. Pre-treatment steps depend on the level of contamination and whether the feedstock has been source separated or not. Separating mixed waste streams requires intensive processing and results in much larger costs. Basic pre-treatment for source segregated OFMSW includes removal of inert contaminants and partial size reduction.

There is a wide range of biogas yields reported from OFMSW depending on the source of the feedstock, how it was collected and the type of AD process employed. For dry batch digestion, biogas yields of between 80 and 125 m^3 biogas/t OFMSW with an average methane content of 60% are quoted by technology providers. Source separated OFMSW is reported as having higher methane yields [38,39] and the resulting digestate is of a higher quality and may have a market value as a soil conditioner. Due to the diverse and changing nature of the OFMSW it is vital to monitor the properties and characteristics of the feedstock. Large quantities of garden waste containing lignin (found in woody material) is not best suited for AD, thus maintaining a feedstock high in water soluble carbohydrates and volatile solids (i.e. VS content of greater than 60%) is important to ensure good biogas yields. The analysis of biomethane from OFMSW is based on a dry batch process similar to that employed by many waste management companies across Europe. A typical facility which processes 50,000 t/a of source segregated OFMSW with a biogas yield of 110 m^3/t feedstock is conservatively assumed in this analysis [40].

3. Analysis – production cost of biomethane

3.1. Biogas plant – capital costs

The capital investment of a biogas plant is a function of feedstock, plant size and technology. The cost of a biogas plant per unit energy output generally decreases with increasing plant size, however in the case of biogas plants producing electricity from CHP, once plant size reaches 1 MW_{el} (1 MW_{el} is equivalent to 2 million m^3 biomethane/a [41]) few cost benefits are gained

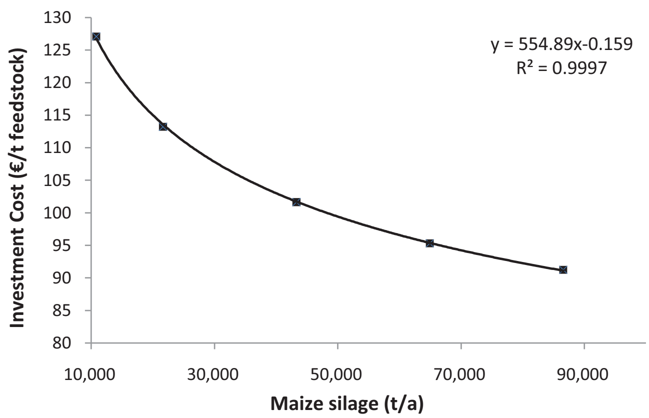

Fig. 1. Investment costs per tonne maize silage with increasing digester size. Data from [25].

through an increase in plant size [17]. The biogas yields per tonne of substrate also have a significant effect on the size of digester needed to produce the target energy output.

Smyth and co-workers reported that a grass silage digester in Austria costs in the region of €100/t/a (excluding the cost of silage storage pits) using a wet two stage CSTR system [20]. Urban and co-workers examined the cost of agricultural based biogas plants in Germany at a range of sizes. A typical biogas plant digesting 90% maize silage and 10% slurry was examined in detail; investment costs per tonne feedstock tend to decrease with increasing plant size, as shown in Fig. 1. Capital costs included for structural works, maize silage storage pits, mechanical and electrical installations, miscellaneous items and decommissioning at end of life.

Biogas plants treating ABP substrates generally necessitate greater capital investment to satisfy the criteria outlined in the ABP regulations [36]. As OFMSW and SWH fall under category 3 of the ABP a particle size reduction of less than 12 mm followed by a pasteurisation step (70 °C for a minimum of 60 min) is required. A comparison of capital costs for different substrates and AD technologies is shown in Table 3.

The capital cost of the biogas plant for scenario 1 is estimated at €110/t/a for grass silage and slurry [20]. An additional investment cost of €30/t/a silage for storage pits is also included. The capital investment for the biogas plant in scenario 2 is estimated at €140/t/a. This is in the cost range of a similar biogas facility treating SHW visited by the authors in Sweden. The cost of a dry batch plant for scenario 3 is estimated at €280/t/a which is more expensive than existing facilities in other EU states. The additional cost includes for higher specifications required by Irish environmental authorities for such waste treatment processes (e.g. batch digesters treating OFMSW must be contained in hermetically sealed buildings).

The cost of purchasing a site for the biogas plant is not included for in this analysis as it is assumed that interested parties such as local authorities, food processing plants, abattoirs, waste collectors, farm co-operatives and others will already possess the land. Typically biogas plants utilising wastes and residues are built near former landfill sites, waste water treatment plants or industrial estates where land prices are relatively low, while biogas plants using energy crops and animal slurry would be located on farms owned by the farmer or farmer co-op. A summary of investment capital costs for the biomethane system is shown in Table 4.

Table 3
Comparison of investment costs for biogas plants in Europe.

Feedstock	AD technology	Quantity	Cost of AD plant
Maize	Wet continuous (Germany)	30,000 t/a	€108/t/a
SHW	Wet continuous (Sweden)	54,000 t/a	€140/t/a
OFMSW	Dry batch (Germany)	25,000 t/a	€220/t/a
OFMSW	Dry batch (Ireland)	50,000 t/a	€280/t/a
OFMSW	Dry continuous (Belgium)	50,000 t/a	€380/t/a

Table 4
Summary of capital investment for biomethane system.

Capital costs (€)	Grass and slurry	SHW	OFMSW
Biogas plant	5,500,000	7,000,000	14,000,000
Silage pit	900,000	–	–
Biogas upgrading plant	1,450,000	1,450,000	1,700,000
Gas grid connection	300,000	300,000	300,000
CNG service station	500,000	500,000	500,000
Total capital cost	8,650,000	9,250,000	16,500,000

3.2. Biogas operating costs

3.2.1. Maintenance, overheads and depreciation

The operational costs associated with biogas production vary from source to source [20,25]. Values in the range of 10–16% of capital are quoted for an agricultural based biogas plant [20]. From discussions with industry the cost of maintenance and overheads for an agricultural biogas plant are in the region of €5/t feedstock (scenario 1). The operation of a SHW digester is expected to require more man-hours than an agricultural plant with additional health and safety requirements such as pasteurisation of feedstock. The additional processing requirements will inevitably lead to higher maintenance costs therefore €10/t is assumed to cover maintenance and overheads for scenario 2. The costs associated with operating an OFMSW digester are expected to be greater than scenario 1 and 2 due to the additional pre-treatment requirements such as waste screening, removal of contaminants and frequent operation of front loading machinery associated with loading and unloading batch digesters, therefore a cost of €25/t is assumed to cover maintenance and overheads for scenario 3. The higher cost of wages in scenario 3 is offset by the lower parasitic demands of the batch system and relatively less maintenance due to the simplicity of design and lack of moving parts. The cost of capital is calculated at a rate of 6% over 15 years. However over the course of the life of the facility some mechanical and electrical elements (boilers, mixers, compressors, etc.) may need replacing. It is conservatively estimated that mechanical and electrical installations account for up to 50% of the total cost of a biogas plant. For this reason a depreciation fund is used to cover 50% of biogas capital costs. Depreciation of capital is calculated using the straight line method. A summary of AD operating costs for the three scenarios is outlined in Table 5.

Table 5
Total annual costs of biogas production.

Annual costs – biogas plant (€/a)	Grass + slurry	SHW	OFMSW
Maintenance and overheads	250,000	500,000	1,250,000
Electrical demand of biogas plant	75,000	75,000	45,000
Thermal demand of biogas plant	50,001	126,424	99,435
Plant operations	375,001	701,424	1,394,435
Substrate cost (€17/t grass silage)	510,000	0	0
Digestate disposal	0	0	200,000
Cost of capital	658,962	720,739	1,441,479
Depreciation fund for M & E	183,055	233,450	466,900
Total annual costs	1,727,388	1,422,163	3,502,813
Income from gate fee	0	1,000,000	3,500,000
Annual cost of biogas production	1,727,388	422,163	2813
Cost of biogas production (€/m³) biomethane	0.82	0.20	0.001

Table 6
Cost of parasitic thermal demand for scenario 2 – SHW.

SHC water	4.184	kJ/kg/°C
Moisture content of feedstock	89%	
Initial temp	15	°C
Pasteurisation temp	70	°C
Temp rise	55	°C
Thermal demand of feedstock	0.205	GJ/t
Boiler efficiency	90%	
Thermal demand	0.228	GJ/t
Total annual thermal energy	11,378	GJ/a
Annual thermal demand	3,160,599	kW_{th} h/a
Cost of wood chips (bulk)	0.04	€/kW_{th} h
Thermal cost	126,424	€/a
Parasitic thermal demand of system	14.8%	

3.2.2. Parasitic demand

Parasitic demand is most significantly influenced by the type of AD technology, substrate properties, operating temperature range of the system (i.e. mesophilic 30–40 °C or thermophilic 50–60 °C) and whether or not the substrate needs to be pasteurised. As the aim of the biomethane system is to produce a valuable commodity with enhanced market value, the parasitic energy requirements should be met by other energy sources. This is an important consideration when examining the lifecycle analysis of the system. In countries where biogas technology is well established it is not uncommon for smaller biogas facilities to supply larger upgrading plants with heat and electricity, thus ensuring low GHG emissions from the system. In this analysis it is assumed that electricity is purchased from a renewable electricity supplier and a low carbon heat source is utilised (e.g. Wood Chip Boiler). In the cost analysis for the three scenarios the cost of woodchips is taken as €0.04/kW_{th} h [20] while the cost of electricity is taken as €0.15/kW_e h.

There is a substantial difference in parasitic demand between wet continuous and dry batch AD plants [42]. In the case of wet continuous two stage systems, it is estimated that electrical demand is approximately 10 kW_e h/t biomass [33]. This includes for pre-treatment such as maceration of feedstock, mixing and pumping. The electrical demand is significantly lower in the dry batch system because of the simplicity of the batch process (technology providers quote 6 kW_e h/t). Higher parasitic thermal energy is required for pasteurising ABP feedstocks (as shown in Table 6), this can lead to large energy demands for substrates with low DS e.g. SHW and slurry.

3.2.3. Cost of feedstock – energy crop vs waste

As shown in Table 5 the feedstock has a large impact on the overall cost of biogas production. Grass silage is a crop that requires good management and cultivation with an associated cost of production attached. A production cost of €17/t of silage is estimated by the Irish Agricultural Institute (Teagasc) [20]. As SHW and OFMSW are regarded as waste products a gate fee for accepting such material can be charged. Discussions with abattoir operators in Ireland indicate the cost of SHW treatment is approximately 20–30 €/t therefore a gate fee of €20/t is assumed for SHW.

The gate fee which OFMSW brings is hugely significant and is linked with the cost of landfill and competition from alternative waste treatment processes. In 2010 the Irish government introduced a landfill levy of €30/t which is part of a strategy to comply with the EU Landfill Directive by encouraging other forms of waste management, such as recycling and mechanical and biological treatment (MBT). Landfill levies are set to rise in the coming years (€50/t in 2011 and €75 in 2012) to accelerate the diversion of biodegradable waste from landfill. The landfill levy (which is essentially a tax) is in addition to the operating costs of the landfill bringing the total cost of landfill to around €150/t (as of 2010). While landfill fees vary from site to site, discussions with the

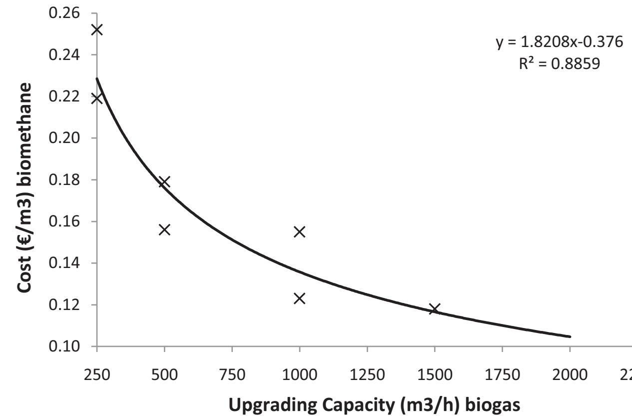

Fig. 2. Estimated unit costs of HWPS upgrading systems.
Data from [25].

industry indicate €100/t is a competitive price for waste disposal at present; however, it is reasonable to assume that these gate fees will not remain constant over a period of 15–20 years. Competition from the composting industry, from other biogas plants as the industry expands, uncertainty in the national waste management strategy and economic recession all add uncertainty to the long term price associated with organic wastes and residues. Therefore a gate fee of €70/t for source segregated OFMSW is chosen as a conservative estimate.

3.2.4. Digestate

Digestate is a significant issue for many biogas plants. The ABP Regulations [36] as interpreted by the State is of huge significance. Digestate from scenario 1 (grass silage and slurry) should be applicable to land (pastureland and tillage). Typically the fertiliser value of the digestate will displace between 35% and 45% of mineral fertiliser [43]. If slurry (prior to AD) is compared with digestate (post AD) the availability of nutrients is doubled in the digestate. There is potentially a significant financial asset associated with digestate; however in this analysis, it is conservatively assumed that the transport and spreading costs of the digestate are covered by the displaced fossil fuel fertiliser requirement. This is also true for paunch content in scenario 2 (SHW). However the same is not true for digestate from OFMSW from a centralised Materials Recovery Facility (MRF). Digestate derived from such a process cannot be applied to agricultural land. The dry fraction must be post composted and is usually used as landfill cover as digestate derived from a MRF process is generally higher in contaminants and toxins and achieving compost of commercial quality is difficult. Digestate from source segregated OFMSW can be used on tillage land as a soil improver (after pasteurisation) or made into garden compost. For the purpose of this paper OFMSW is assumed to be source segregated and the digestate made into garden compost at a small cost of €200,000/a (i.e. €4/t of starting material).

3.3. Biogas upgrading costs

A range of costs (€0.11–0.25/m^3 biomethane) have been quoted in literature for upgrading systems treating from 100 to 1000 m^3/h raw biogas [19,20,24]. The cost of HPWS upgrading systems can vary between technology providers; however as shown in Fig. 2 the cost is most significantly influenced by the size of the upgrading plant. A significant decrease in cost can be seen from 250 m^3/h to 1000 m^3/h, however there is little cost benefit in increasing plant size beyond 1500 m^3/h. Electricity usage which is required for compression, cooling and pumping, accounts for the largest portion of operating costs in a HPWS

Table 7
Cost of upgrading for three scenarios.

Scenario	1	2	3
Biogas production (m^3/h)	460	468	688
Upgrading capacity (m^3/h)	500	500	750
Estimated cost of upgrading (€/m^3)	0.176	0.176	0.151
Upgrading capacity used (%)	92%	94%	92%
Total cost of upgrading (€/m^3)	0.19	0.19	0.16

system. Technology providers indicate electrical use is between 0.25 and 0.33 $kW_e\,h/m^3$ raw biogas input. Capital investment costs for HPWS upgrading systems range from €1.35–2 million for capacities of between 250 and 1000 m^3/h [25,26].

It is important to note that the upgrading costs per m^3 biomethane shown in Fig. 2 are based on optimum operating conditions (i.e. max biogas throughput for given plant capacity and upgrading time efficiency of approximately 90%). To ensure economical upgrading efficiency, biogas production rates should match the upgrading capacity of the plant and any down time periods should be kept to a minimum as the cost per unit rises sharply with decreasing time efficiency. Costs shown in Fig. 2 include the cost of capital and operational costs such as electricity, water, thermal gas treatment and plant maintenance.

For scenario 1 and 2 a 500 m^3/h HPWS plant is employed, while a capacity of 750 m^3/h plant is chosen for scenario 3 to cater for the higher biogas yields. To account for different biogas production rates in each scenario, the upgrading capacity used is also considered as shown in Table 7. Typically upgrading plants have some inbuilt flexibility to cater for increased biogas loads (e.g. a 500 m^3/h upgrading plant has some additional capacity to treat up to 600 m^3/h). The formula shown in Fig. 2 is used to estimate the cost of HPWS upgrading systems.

3.4. Compression and distribution

Once the biogas has been upgraded to biomethane it must be transported or stored for later use. There are two main avenues, the biomethane can be compressed to approximately 250 bar, stored on-site and later transported to a service station or alternatively the biomethane can be injected into the gas grid and transported to an off-site compression and service station. The gas distribution grid operates at approximately 4.2 bar so no additional compression is needed for injection to the distribution grid as HPWS upgrading plants typically pressurise biomethane up to 7–9 bar [20].

In some European states such as Sweden on-site compression, storage and distribution via pressurised containers is chosen out of necessity as the natural gas grid is limited to the west of the country. As shown in Fig. 3, Ireland has an extensive natural gas network; injection of biomethane into the natural gas grid could be a more advantageous supply route with respect to energy efficiency and associated environmental benefits [28]. At present a full pricing scheme for grid injection is not available in Ireland and the finer details of accounting for biomethane (with respect to meeting RES targets) once in the grid have yet to be finalised. However, there are a number of European states (e.g. Germany and Holland) which are successfully injecting biomethane into the national grid, leading to a sharp rise in the development of biogas upgrading plants since the introduction of grid injection. Gas grid injection is chosen as the mode of distribution to suppliers in this analysis to allow for greater energy efficiency and flexibility (e.g. gas transport via pressurised pipeline is considerably more energy efficient than electrical transport via high voltage cables).

Connection to the gas grid would allow for the blending of biomethane with natural gas to produce BioCNG. From discussions with the industry, the cost of connection to the gas grid can vary widely and depends on distance to the network, ground conditions,

Fig. 3. Map of Ireland's Natural Gas Grid (Bord Gáis Networks http://www.bordgais.ie/).

Table 8
Summary of biomethane production costs for three scenarios.

Total production cost in €/m^3 biomethane	Grass and slurry	SHW	OFMSW
Biogas production	0.822	0.202	0.001
Biogas upgrading	0.191	0.188	0.165
Compression and distribution	0.149	0.149	0.135
Cost of biomethane production (€/m^3)	**1.162**	**0.540**	**0.300**
VAT @ 21%	0.244	0.113	0.063
Cost of biomethane production including VAT (€/m^3)	**1.406**	**0.653**	**0.363**

the type of pipe, etc. It is therefore assumed in this analyses that the biomethane plants are located within 0.5 km of the distribution gas network to keep connection costs at a minimum. Smyth and co-workers estimated the capital cost of grid connection at €200,000 while Urban et al., estimated a higher cost of connection of approximately €300,000 including a 50% investment subsidy for network connection which biomethane suppliers are entitled to under German regulations (GasNZV) [25]. The latter is assumed as the capital cost of grid connection.

The cost of building a biomethane/BioCNG service station is estimated at €500,000 [41]. Biomethane used as a transport fuel needs to be compressed to approximately 250 bar prior to fuelling. Therefore, the cost of compression to 250 bar is included for in the analysis to allow for comparison with other fuels (i.e. petrol and diesel). A compression cost of €0.11/m$_n^3$ biomethane is taken in the analysis; this includes the cost of electricity used in compression, annual cost of capital, maintenance and overheads. Compression of biomethane to 250 bar also requires significant electrical input, a value of 0.35 kW$_e$ h/m^3 biomethane is taken in this analysis [19]. A summary of total production costs for each scenario is shown in Table 8.

3.5. Cost sensitivity analysis

It is clear that for each scenario the cost of biomethane is based on a number of key assumptions. Of these the biogas yields per tonne of feedstock and the gate fees associated with ABP substrates have the largest impact on production costs. Table 9 shows the effects of cost sensitivity for the 3 scenarios. The cost of biomethane production in scenario 3 is largely reliant on the gate fee which is associated with OFMSW. The baseline case assumes €70/t giving an overall production cost of €0.30/m^3. If the gate fee is decreased by 10% to €63/t the overall cost of production increases by 33%. If no gate-fee is received, the cost of production jumps to €1.35/m^3 which is 4.5 times the baseline cost. This underlines the importance of gate-fees to waste treatment systems. The cost of grass silage also has a significant impact on biogas production; according to the Irish Agricultural Institute (Teagasc) there is a range of costs associated with grass silage production. In the baseline scenario a cost of €17/t was chosen, however it is possible that production costs could be up to 50% more depending on soil type, farming practises etc. therefore a cost of €25/t is taken as the upper bound cost in the sensitivity analysis. This has the effect of increasing the cost of biomethane from grass and slurry by 10%. The biogas yield of the substrate also has a significant effect on the overall production cost of biomethane; this is especially important for scenario 1, by increasing the methane yield of grass silage by 10% (i.e. from 300 to 330 m^3 CH_4/tVS) the cost of biomethane can be reduced by almost 8%. Increasing the cost of biogas upgrading has relatively less impact; however as discussed earlier maintaining biogas throughput to match operational capacity is necessary to maintain cost efficiency.

Table 9
Impact of parameter changes on production costs.

Cost of biomethane production (€/m^3)	Scenario 1	Scenario 2	Scenario 3
Baseline costs	1.16	0.54	0.30
Gate-fee – 10%	–	0.59	0.40
Silage production costs €25/t	1.28	–	–
Upgrading costs + 10%	1.18	0.56	0.32
Methane yields + 10%	1.07	0.50	0.28

4. Discussion of results

4.1. Discussion of production costs

As shown in Table 8 there is a significant difference in the cost of biomethane from the three scenarios. Biomethane from scenario 3 (OFMSW) is the cheapest to produce at a cost of approximately €0.30/m^3. This is highly profitable but is largely based on income from gate fees which may change over time. A production cost of €0.54/m^3 for scenario 2 (SHW) also shows great potential for profit as a transport fuel while the cost of biomethane production from scenario 1 (grass and slurry) at €1.16/m^3 (excluding tax) is also competitive compared with current transport fuel prices. Smyth and co-workers [20] reported the cost of producing biomethane from grass silage was €1.02–1.21/m^3 depending on operational costs. As shown in Fig. 4 biomethane from SHW and OFMSW (scenario 2 and 3) can only satisfy a relatively small percentage of final transport energy demand due to the limited resources available. Grass and slurry on the other hand are ubiquitous and have the potential to meet and even exceed Ireland's RES-T 10% targets by 2020 because of the large quantities available. If the 10% RES-T target is to be met with biomethane, agricultural feedstocks will play a significant role. Of the 10% RES-T target OFMSW accounts for only 6.4%, SHW 7.6%, while grass and slurry will fulfil the remaining 86%, therefore the weighted cost of biomethane production to meet the 10% target is dominated by the cost of biomethane from grass and slurry (scenario 1). The production cost of biomethane to meet the 10% target is estimated at €1.06/m^3 biomethane excluding taxes (€1.28/m^3 including taxes). However as EV's and liquid biofuels are expected to meet some of the RES-T requirement, biomethane may not have to meet the full 10% the RES-T target. Fig. 5 shows the cost of biomethane production at increasing shares of RES-T.

Gas used as a transport fuel is currently exempt from excise duty in Ireland, however value added tax (VAT) for transport fuel is charged at the rate of 21%. The total cost of biomethane including VAT at increasing RES-T is shown in Table 10. The EU Renewable Directive [4] suggests that biogas from OFMSW and slurries as a compressed natural gas effects 75–81% reduction in emissions of the whole life cycle analysis of the fuel it displaces. Therefore

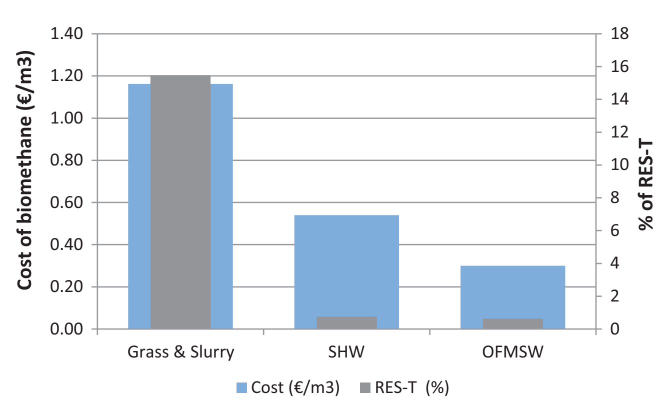

Fig. 4. Cost of biomethane (ex. taxes) from three scenarios and potential for RES-T.

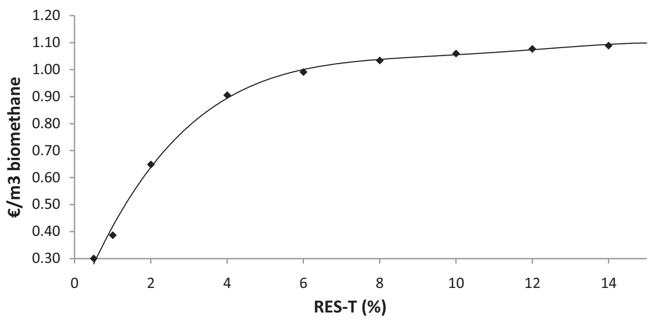

Fig. 5. Weighted cost of biomethane production (ex. taxes) with corresponding RES-T share.

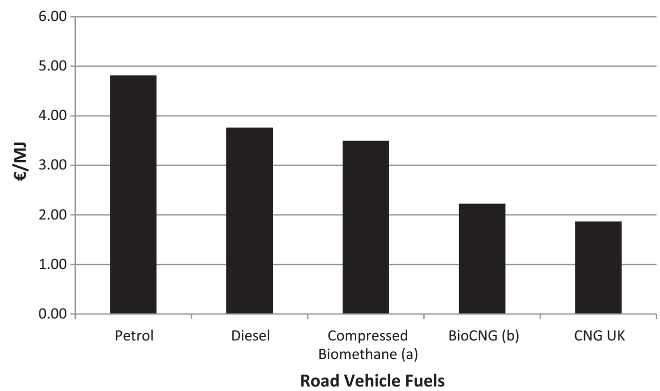

Fig. 6. Cost comparison of vehicle fuels per unit energy. [a]Cost of biomethane production including VAT meeting the 10% RES-T target. [b]BioCNG = 80% CNG and 20% BioCNG.

assuming that biomethane displaces 75% of CO_2 per litre of diesel equivalent and that diesel produces 2.69 kg CO_2/L [34], a CO_2 saving of 2.02 kg CO_2/L diesel is achieved. Carbon tax is set at €25/t CO_2 in Ireland as of January 2011, this equates to a saving of €0.05/L diesel equivalent.

4.2. Developing a biomethane market for RES-T

According to Howley and co-workers [1] public vehicles accounted for 4.9% of total road transport energy in 2009. By meeting public transport energy with biomethane from wastes and lignocellulosic material and allowing for the associated double credit, 9.8% RES-T could be meet, thus allowing Ireland meet its 2020 target. The argument for using CNG vehicles in cities to reduce particulate matter pollution from diesel engines and thus improve air quality is already providing a stimulus for conversion of public transport vehicles to CNG in many countries; therefore, by using BioCNG a cleaner, more environmentally friendly, more competitive transport fuel can be achieved.

Based on the price of CNG in the UK (€0.71/m^3) and the cost of biomethane (including VAT) at 10% RES-T (€1.28/m^3), a BioCNG blend of 20% biomethane and 80% NG would cost €0.82/m^3. This presents a significant cost saving over current transport fuel prices (average prices in February 2011 accord to AA Ireland [44]: petrol 144.5 c/L, diesel 138.5 c/L). Biomethane and especially BioCNG blends are competitive on a cost per unit energy bases as shown in Fig. 6. Thus the renewable energy potential from grass and slurry can be realised along with environmental and security of supply benefits while the consumer has the chioice of a competitive transport fuel.

The obvious flaw in developing a biomethane transport industry in Ireland is the lack of CNG vehicles and service stations. In order for a biomethane industry to develop in Ireland a captive fleet of CNG vehicles and biomethane/CNG service stations would be required. In this regard government policy to encourage the use of CNG vehicles in replacing existing vehicles in the public bus fleet would provide a stimulus for market development. A market for a competitive transport fuel in the form of BioCNG is quite promising in bringing environmental, economical and employment benefits to the country. There are now over 12 million CNG vehicles worldwide; this is set to rise due to cost efficiency and improved air quality. The use of compressed biomethane and blended BioCNG is also increasing, e.g. in Sweden there is approximately 17,000 CNG vehicles utilising a BioCNG fuel that contains more than 55% biomethane. The proportion of biomethane used in the gaseous fuel has increased over time and is set to further increase in the future. Ireland has approximately 2 million road vehicles, the potential number of vehicles which could be fuelled by 15 PJ/a biomethane (Table 1) would equate to 390,000 cars/a (i.e. fuel used by a petrol car travelling 18,000 km/a at a fuel efficiency of 7 km/L). This equates to 19.5% of the national vehicle fleet.

Table 10
Weighted cost of biomethane including taxes at increasing RES-T penetration.

RES-T (%)	Cost of production (€/m^3)	VAT @ 21%	Total cost including VAT (€/m^3)
2	0.65	0.14	0.78
4	0.91	0.19	1.10
6	0.99	0.21	1.20
8	1.03	0.22	1.25
10	**1.06**	**0.22**	**1.28**
12	1.08	0.23	1.30
14	1.09	0.23	1.32
16	1.10	0.23	1.33

The development of a biomethane market in Ireland needs stimulus and should be lead by targeted Government policy. Incentives must be associated with public service vehicles such as buses, taxis and local authority vehicles. Subsidies must be provided to allow the ratio of vehicles to CNG service stations reach a ratio that allows financial sustainability. This can be achieved through subsidy of CNG service stations, CNG powered vehicles and/or the mandating of gaseous transport fuel. Technical standards, regulations and specifications are required for biomethane injection. At the moment, Ireland has no clear road map to meet its commitment of 10% RES-T in 2020. The benefit of a biomethane industry is an indigenous transport fuel that will help Ireland to meet the RES-T targets, significantly lessen Ireland's dependence on imported fossil fuels, allow compliance with the Landfill Directive, and reduce air pollution. The natural gas grid will provide an efficient cheap means of transporting biomethane to fuel stations. The gas grid in Ireland is connected to over 40% of homes; this may allow for a home-fill system for CNG vehicles.

5. Conclusions

As petrol and diesel prices at the pumps continue to rise, biomethane and BioCNG present an opportunity for a sustainable, economical transport fuel that can realistically meet Ireland's RES-T targets and provide a much needed stimulus for an ailing economy. The cost of biomethane produced from grass and slurry is highest but is also the most reliable and plentiful resource (€1.41/L diesel equivalent allowing for 21% VAT) and should be encouraged by government policy. The weighted cost of biomethane to meet 10% RES-T is €1.28/L diesel equivalent; this is almost 8% cheaper than the price of diesel in February 2011. Biomethane has an advantage over liquid fuels as gas is not presently subject to excise duty. Biomethane from organic wastes and lignocellulosic material

can save approximately 75% CO_2 of diesel emissions and therefore should be exempt from carbon tax. The cost of biomethane produced from organic wastes such as OFMSW and SHW is very competitive at 36 c/L and 65 c/L diesel equivalent respectively. However OFMSW is limited to approximately 0.64% of total final energy in transport while SHW can provide an additional 0.76%; thus at a scale of 1.4% RES-T biomethane will cost a minimum of 52 c/L diesel equivalent. To achieve 10% RES-T, biomethane will cost a minimum of €1.28/L diesel equivalent. Gaseous fuel can be made cheaper by considering BioCNG (e.g. 20% biomethane with 80% natural gas at €0.82/L diesel equivalent) with the cheaper fossil fuel subsidising the more expensive biomethane. Biomethane from organic wastes which earn additional income through gate fees may present the cheapest option for initial RES-T penetration (up to 1.4% RES-T), however for long term stability and increased RES-T share, investment in biomethane from grass silage and slurry should be encouraged.

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